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# Dust Polarization From Starlight Data

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**Abstract.**
We present a statistical analysis of the interstellar medium (ISM) polarization from the largest compilation available of starlight data, which comprises $\sim 5500$ stars. The measured correlation between the mean polarization degree and extinction indicates that ISM dust grains are not fully aligned with the uniform component of the large-scale Galactic magnetic field. Moreover, we estimate the ratio of the uniform to the random plane-of-the-sky components of the magnetic field to be $\mathbf{B_u}/\mathbf{B_r} \approx 0.8$. From the analysis of starlight polarization degree and position angle we find that the magnetic field broadly follows Galactic structures on large-scales. On the other hand, the angular power spectrum $C_\ell$ of the polarization degree for Galactic plane data is found to be consistent with a power-law, $C_\ell \propto \ell^{-1.5}$ (where $\ell \approx 180^\circ/\theta$ is the multipole order), for angular scales $\theta > 10'$. We argue that this data set can be used to estimate diffuse polarized emission at microwave frequencies.

## INTRODUCTION

The Milky Way Galaxy emits polarized radiation at radio, mm-wave, far-infrared and optical wavelengths (see e.g, [4] for a recent review). The different mechanisms which cause the emission to be polarized at each of these wavelengths are all related to the Galactic magnetic field. Therefore the measurement of the polarized Galactic emission should yield valuable information on our Galaxy's magnetic field (see e.g, [32, 19, 14]).

Observed starlight polarization is believed to be caused by selective absorption by magnetically aligned interstellar dust grains along the line of sight. Since these measurements are limited by dust extinction, they provide us with a picture of the magnetic field only in the vicinity of the sun. Despite this limitation, recent analyses of such measurements (see [13] and references therein) suggest that they do contain information about the uniform and random components of the magnetic field on large scales. In particular,starlight polarization vectors trace the plane-of-the-sky projection of the Galactic magnetic field [32] and measurements of polarization for stars of different distances reveals the 3D distribution of magnetic field orientations averaged along the line of sight.

The Milky Way magnetic field has also been studied from measurements at far-infrared and mm wavelengths [18, 26]; see also [19, 14] for recent reviews. However, the regions surveyed correspond to few very small regions, largely dense dark clouds, mostly in the Galactic plane and they they reflect rather local distortions of the large-scale magnetic field, while a global view has only been obtained for external spiral galaxies similar to our own [32].

At optical wavelengths many polarization measurements do exist, which offer an alternative view to our Galaxy. We shall present below the most complete compilation to date of starlight polarization observations. This analysis will allow us to extract basic information on the large scale statistical properties of the polarization field in the visible. We do this by studying the correlations between stellar parameters and computing the angular power spectrum of the optical polarization degree from Milky Way stars. A more detailed discussion of the analysis and results presented here is given in [7].

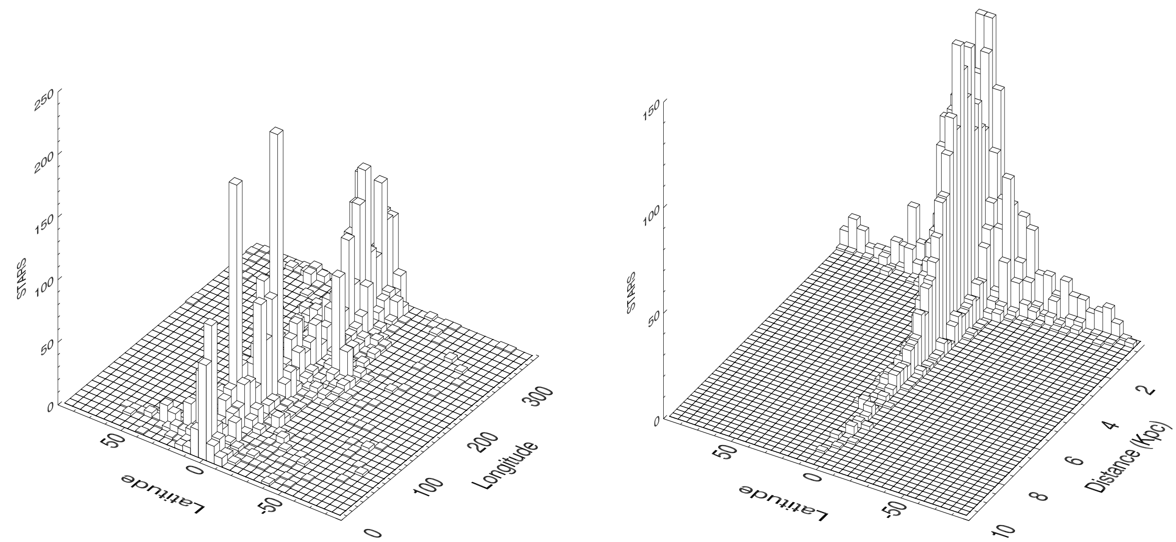


**FIGURE 1.** Distribution of starlight polarization data in Galactic longitude and latitude bins (*Left*) and distance and latitude bins (*Right*) for the subsample of 5513 stars analyzed.

## DATA

The starlight polarization data used in this analysis is taken from the compilation by Heiles (see [13] for details and references to the original catalogues; see also [7]). This compilation includes data from 9286 sources taken from a dozen of catalogs combining multiple observations, providing accurate positions and reliable estimates for extinction and distance of stars. From this catalog, we have selected a subsample of 5513 stars (60% of the data) based on the following criteria: (1) the degree and angle of polarization are given, (2) small absolute error in the polarization degree ($<$ 0.25%) and (3) a (positive) extinction is given. All the stars in the Heiles compilation fulfilling the above requirements also have quoted distance with an estimated 20 % error for most of the sources [13].

| Latitude | Distance | Stars (%) | P(%) | E(B-V) |
|---|---|---|---|---|
| Low Latitude | Total | 4114(75) | 1.69 | 0.49 |
| | Nearby | 1451(26) | 0.94 | 0.29 |
| | Distant | 2663(48) | 2.09 | 0.60 |
| High Latitude | Total | 1399(25) | 0.45 | 0.15 |
| | Nearby | 1315(24) | 0.42 | 0.14 |
| | Distant | 84(1) | 0.89 | 0.26 |

**Table 1.** Mean Stellar Parameters. High latitude (low latitude) means $|b| > 10°$ ($|b| < 10°$) and nearby (distant) denotes d $<$ 1 Kpc (d $>$ 1 Kpc). The quantities between brackets denote amount % of all stars in the sample.

Fig 1 shows the distribution of sources in our subsample for data binned in Galactic coordinates (left panel) as well as in distance and latitude (right panel). As shown in the latter, practically all high latitude ($|b| > 10°$) stars are nearby (d $<$ 1 Kpc). Within the Galactic plane one can find relatively distant stars, though the vast majority are within 2 Kpc. Therefore, this is a rather local sample. This is also clearly displayed in the starlight polarization map of the subsample of 5513 stars analyzed (see Fig 2).

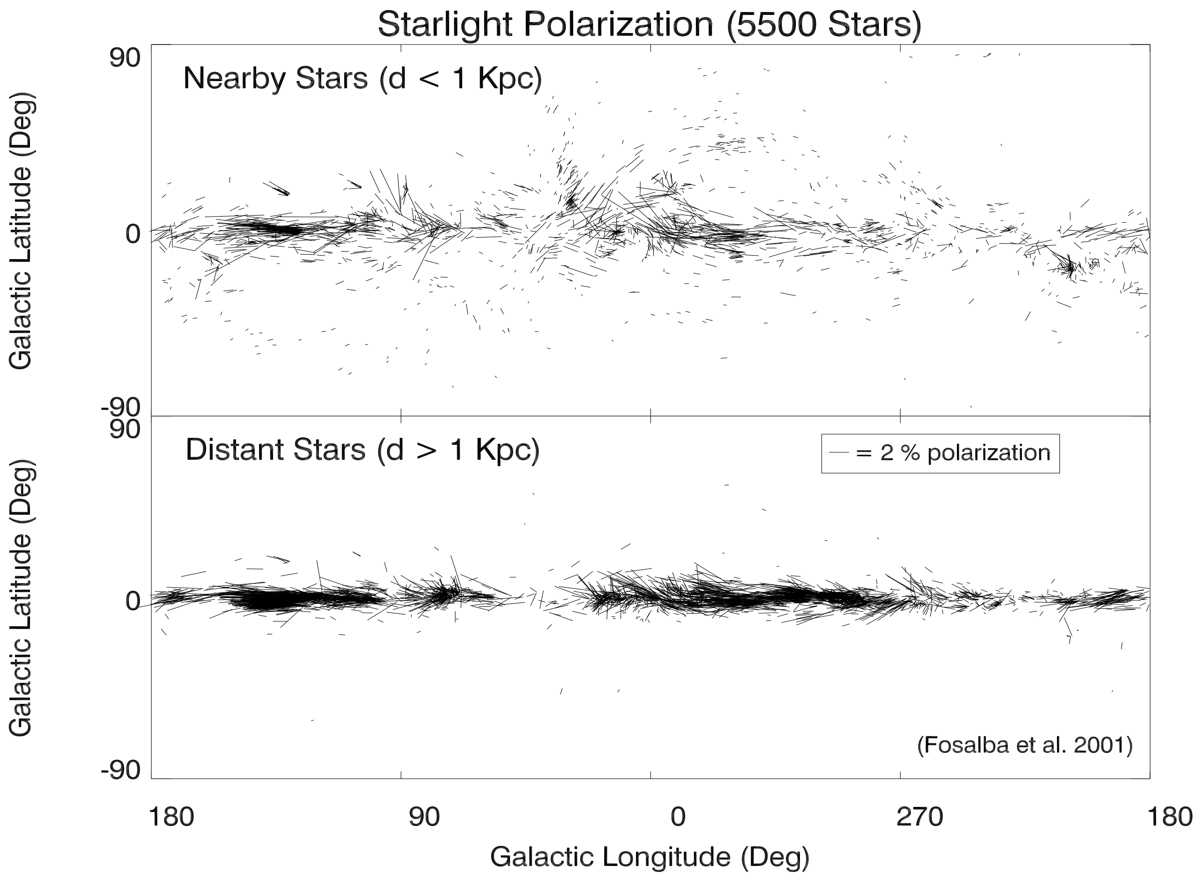


**FIGURE 2.** Starlight polarization vectors in Galactic coordinates for a sample of 5513 stars. The upper panel shows polarization vectors in local clouds, while the lower panel displays polarization averaged over many clouds in the Galactic plane. The length of the vectors is proportional to the polarization degree and the scale used is shown in the lower panel.

A more quantitative account of this fact is summarized in Table 1, where we give the mean stellar parameters (i.e, polarization degree P(%) and extinction as measured by the color excess E(B-V)) in the subsample as a function of latitude and distance. It is seen that low-latitude stars have large values of the polarization degree P(%) $\approx$ 1.7, and extinction E(B-V) $\approx$ 0.5, while high-latitude sources exhibit significantly lower values, P(%) $\approx$ 0.5, E(B-V) $\approx$ 0.15. Polarization vectors (defined with respect to Galactic coordinates) are typically oriented along the Galactic plane ($\theta_p \approx 90^\circ$) although a more detailed analysis reveals a rich spatial distribution (see Fig 2 and discussion below).

## STARLIGHT POLARIZATION AND GALACTIC MAGNETIC FIELD

It is generally accepted that grains in diffuse interstellar gas tend to be aligned with their major axes perpendicular to the magnetic field. [1] According to this picture, the electric field of radiation transmitted by an interstellar dust grain is less absorbed along the grain minor axis and therefore polarized in that direction which is parallel to the external magnetic field orientation. Thus, polarized starlight radiation vectors are oriented parallel to the Galactic magnetic field [32]. This polarization mechanism is usually referred to as *differential absorption*.

Since starlight polarization vectors are only seen as projected in the plane of the sky, they just give us direct information on the plane-of-the-sky projection of the Galactic magnetic field orientation. As shown in Fig 2, there

[1] There is no consensus as yet in relation to what alignment mechanism is the dominant in the interstellar environment [23], [25]. Currently, the radiative torque mechanism seems the most promising [5, 6].

is a strong net alignment of starlight polarization vectors averaged over many clouds with the Galactic plane structures (see lower panel) as well as a clear alignment with the spherical shell of Loop 1 as seen from the polarization vectors in local clouds (see upper panel). This is in remarkable qualitative agreement with previous studies, namely [31] (based on the catalog of [1]) and [32]. In fact, for an homogeneous distribution of intervening dust, the larger the path-length starlight travels to reach the observer, the larger the polarization degree and extinction are expected to be. According to this simple picture, regions with measured low starlight polarization degree (and extinction) correspond to the *local* ISM, while highly polarized ISM regions are observed in the line-of-sight to distant stars. This is actually observed in the sample of starlight data we have analyzed (see Fig 2). Most of the nearby stars (d $<$ 1 Kpc) are found at high Galactic latitudes, while distant sources (d $>$ 1 Kpc) lie mainly in the Galactic plane.

On the other hand, the spatial distribution of the polarization degree and position angle are expected to be highly correlated and this is also observed in the starlight polarization map (Fig 2), where highly polarized regions exhibit position angles aligned with the Galactic plane. There is a (sinusoidal) *modulation* of this correlation with Galactic longitude due to a projection effect: one observes the plane-of-the-sky projection of the polarization vectors that are aligned with the various Galactic spiral arms (see right panel in Fig 3).

In summary, we find evidence that *there is a net alignment of the magnetic field (as seen from its plane-of-the-sky projection) with Galactic structures on large-scales*. However, we stress that the full reconstruction of the 3D magnetic field orientations (and strength) requires additional complementary data from radio (synchrotron), sub-mm/IR (dust) observations and rotational measures from distant pulsars (see [32, 10, 11] and references therein).

## POLARIZATION DEGREE AND EFFICIENCY OF MAGNETIC FIELD ALIGNMENT

As discussed in the previous section, it follows from simple arguments that the starlight polarization degree and extinction should be correlated. We do find such correlation for individual sources in our sample. However, *on the mean*, the measured correlation, P(%) = 0.39 E(B-V)$^{0.8}$ (see top panel in Fig 3) has a lower amplitude than what is expected from complete dust-grain alignment from homogeneous magnetic fields [20], P(%) = 9 E(B-V) (see lower panel in Fig 3). The observed roughly linear correlation for individual sources is in agreement with measurements at 2.2 $\mu$m [20] & 100 $\mu$m [17]. The fact that starlight data exhibits a lower polarization degree as a function of extinction than the theoretical upper limit, suggests that *either the grain alignment is not optimal or the Galactic magnetic field has a significant random component*.

In general, we can decompose the total magnetic field as the addition of a *uniform* (coherent), $\mathbf{B_u}$, and a *random* (incoherent) $\mathbf{B_r}$ component. A random component of the magnetic field smears to some degree the correlation introduced by the uniform component [20]. This smearing effect is likely to affect the observed stars as supported by the high degree of incoherence observed for the starlight position angle. This is especially evident from nearby sources (top panel in Fig 2). Assuming that the depolarization is mainly caused by the randomness of the magnetic field, one can relate the observed polarization degree to the ratio of uniform to random plane-of-the-sky components of the underlying magnetic field (see e.g, [12]). In particular, assuming Burn's model [3], one finds for the starlight sample, $\mathbf{B_u}/\mathbf{B_r} \approx 0.80$, for E(B-V) $\approx 1$, corresponding to distant stars as an unbiased estimate of the ratio. This value is roughly consistent with previous estimates from starlight data (see [12] for a review and references therein): $\mathbf{B_u}/\mathbf{B_r} \approx 0.68$, and is typically larger than estimates from synchrotron polarization or rotational measures of distant pulsars. The discrepancy can be explained as every data set basically samples a different component of the interstellar medium: pulsars mainly trace the warm ionized medium, starlight data samples primarily the neutral media while synchrotron data seems to sample all components [12].

## LARGE-SCALE PATTERN OF THE POLARIZED ISM: A POWER SPECTRUM ANALYSIS

The large-scale statistical properties of the ISM polarization from *absorption* of starlight by dust grains might give direct statistical information on the polarized diffuse *emission* by dust: if the grains that extinct starlight and emit constitute the same grain population, the power spectrum of starlight polarization degree is directly related to the power spectrum of polarized emission from dust. Starlight polarization is caused by aligned grains with sizes $10^{-4} > a > 10^{-5}$ cm [21], which generate polarized emission in diffuse media [27], [25]. Therefore if aligned grains

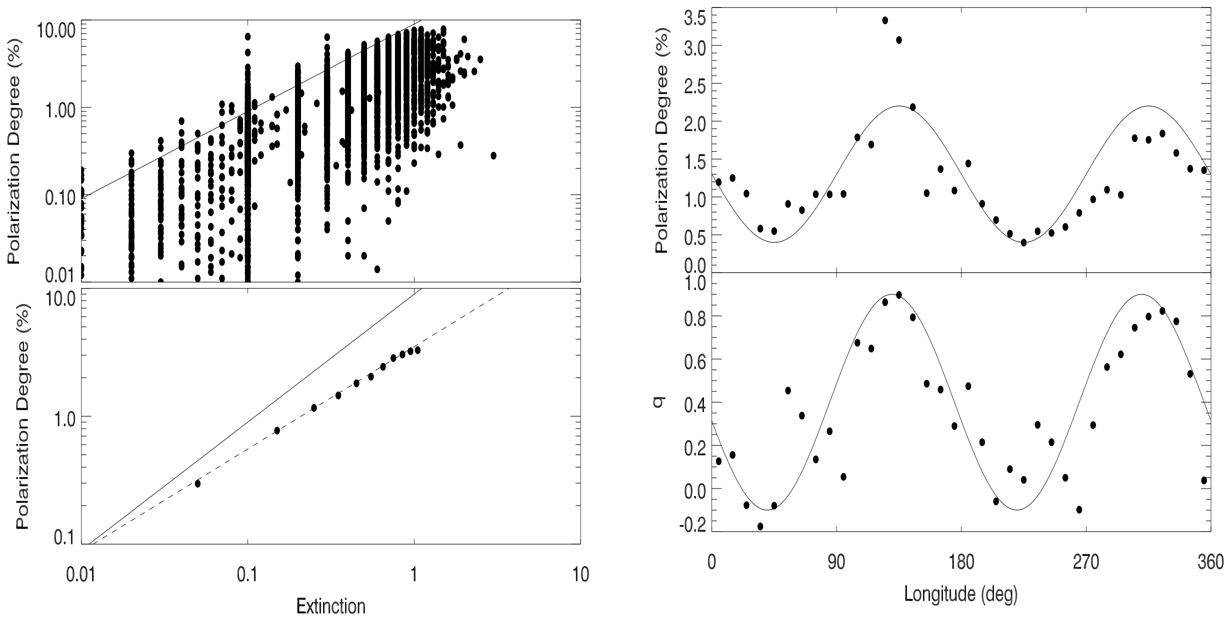


**FIGURE 3.** (*Left*) Correlation between polarization degree P(%), and extinction E(B-V). Upper panel shows all individual sources while lower panel displays data averaged in extinction bins. Solid line shows the theoretical upper limit, P(%) = 9 E(B-V), for completely aligned grains by external (regular) magnetic fields. Dashed line in lower panel shows P(%) = 0.39 E(B-V)$^{0.8}$, which is a good fit to the data up to E(B-V) $\approx$ 1. (*Right*) Starlight Polarization Degree (top panel) and the parameter $q = \cos 2(\theta_p - 90^\circ)$ (bottom panel) for data averaged in 10° longitude bins.The solid line shows a best fit to a sinusoidal dependence.

in diffuse medium have the same temperature the power spectrum of the starlight polarization should be identical to the spectrum of the polarized continuum from dust in the FIR range (e.g, 100$\mu$m).

In a fully-sampled map, the two-point correlation function $\xi(\theta)$ of the scalar field S is simply related to the angular power spectrum (APS):

$$\xi(\theta) = < S(\mathbf{q_1}) S(\mathbf{q_2}) > = \sum_{\ell} \frac{\ell + 1/2}{\ell(\ell+1)} C_\ell P_\ell(\cos\theta) \tag{1}$$

where the APS, $C_\ell$, estimates autocorrelations of the field at an angular scale $\theta \approx 180^\circ/\ell$, $\ell$ being the so-called multipole order.

We have focused on Galactic plane data ($|b| < 10^\circ$) as it concentrates most of the sources in the sample and therefore makes the statistical analysis more reliable. To compute the APS, we use a *hybrid* approach, that we shall call the *improved correlation function analysis*, that combines the advantages of real (or pixel) and harmonic (or multipole) space approaches [28, 29]. For this purpose we first compute the two-point correlation function, $\xi(\theta)$, of the polarization degree data using a quadratic estimator where shot-noise and edge effects intrinsic to the starlight data set are adequately corrected in pixel space. [2]

Our analysis shows that the starlight polarization degree S is well fitted by a power-law behavior, $C_\ell \propto \ell^{-1.5}$ for $\ell < 1000$ (where the multipole order $\ell \approx 180^\circ/\theta$) which translates into angular scales $\theta > 10'$ (see left panel in Fig 4). This is approximately the pixel resolution scale used, $3.5'$. We have assessed how the above results are affected by the *clustering* or non-Gaussianity in the distribution of sources by simulating a *mock starlight map* for the polarization degree (see right panel in Fig 4). We found that the efficiency with which one measures the power spectrum of the underlying densely-sampled signal is not significantly altered by the clustering of the sources, although for the actual data, that is non-Gaussian distributed, shot-noise dominates at smaller scales (i.e, in the direct harmonic approach, $C_\ell = Constant$ for a larger multipole in the actual data than in the simulation; see green lines in Fig 4) and the estimated power spectrum is noisier than the simulated random-Gaussian case (see blue lines in Fig 4).

[2] This method uses the *anafast* program of the HEALpix package [9] for the fast computation of the APS.
See `http://www.eso.org/science/healpix/`

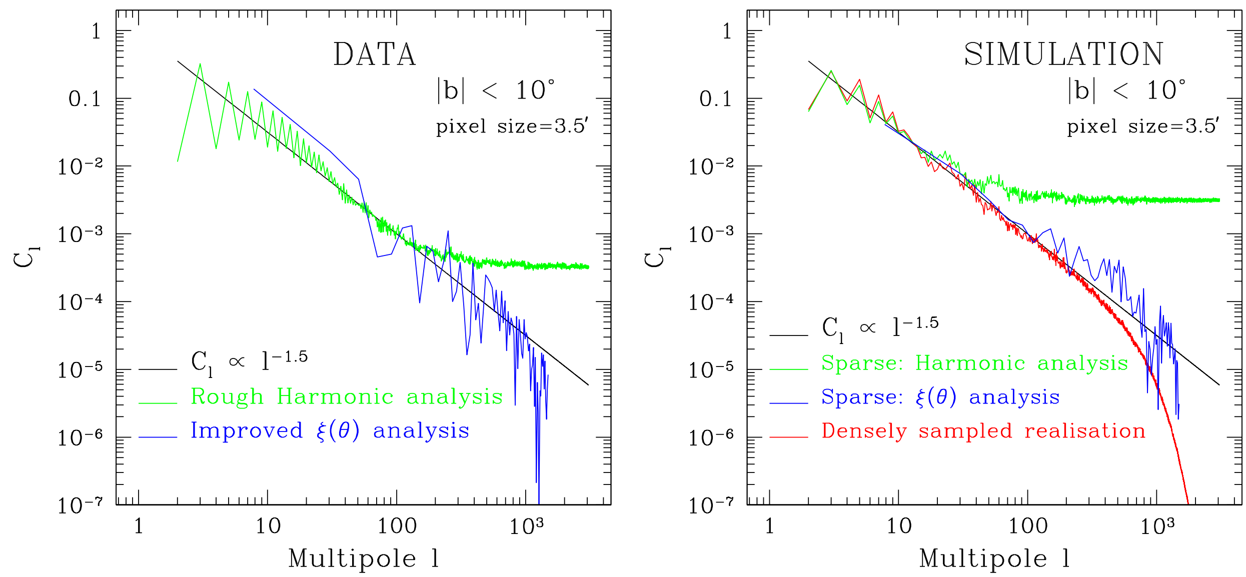


**FIGURE 4.** Angular power spectrum of the starlight polarization degree map in the Galactic plane, $|b| < 10°$, for the real data (*Left*) and the simulated mock catalog (*Right*). *Rough harmonic analysis* denotes a direct approach in harmonic space, while *improved* $\xi(\theta)$ *analysis* is a hybrid approach (uses techniques both in pixel and harmonic space) that corrects for shot-noise and edge effects. As a reference, the red line shows a densely sample realization of $C_\ell \propto \ell^{-1.5}$.

The above results provide evidence that the use of the polarization degree of the ISM as sparsely-sampled from lines-of-sight to several thousand (Galactic-plane) stars allows a clean reconstruction of the APS of an underlying *homogeneously sampled* (continuum) polarization degree of the ISM. In particular, we find that the ISM polarization degree in the continuum has the same APS slope than that measured from sparsely-sampled data, $C_\ell \propto \ell^{-1.5}$. It is interesting to note that this slope is consistent with that estimated from surveys of polarized Galactic synchrotron emission [30, 2], and the possible underlying common cause certainly deserves investigation. In a future work [8] we shall discuss how to use the starlight data set to estimate diffuse polarized emission at microwave frequencies by relating polarization by differential absorption in the optical with polarized emission in the sub-mm/FIR using dust grain alignment models [15, 16]. An accurate knowledge of such polarized emission is a critical issue in the process of component separation in cosmic microwave background experiments [27, 25].

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    The data is publicly available by anonymous ftp at vermi.berkeley.edu. See pol15.out (compilation of data), and pol1.ps (description and references for the compiled data) in directory pub/polcat . It has also been recently made available through the web-sites:
    `http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=II/226`
    `http://adc.gsfc.nasa.gov/viz-bin/VizieR?-source=II/226`
    However, note that in these http addresses, no starlight extinction information is provided.
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